

Advanced Radioisotope Power Sources for Future Deep Space Missions

Erik N. Nilsen

*Member of the Technical Staff, Jet Propulsion Laboratory
California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109*

(818)354-4441; Erik.N.Nilsen@jpl.nasa.gov

Abstract. The use of Radioisotope Thermoelectric Generators (RTGs) has been well established for deep space mission applications. The success of the Voyager, Galileo, Cassini and numerous other missions proved the efficacy these technologies in deep space. Future deep space missions must also rely on the availability of Advanced Radioisotope Power System (ARPS) technologies to accomplish their goals.

In the Exploration of the Solar System (ESS) theme, several missions are in the planning stages or under study that would be enabled by ARPS technology. Two ESS missions in the planning stage may employ ARPS. Currently planned for launch in 2006, the Europa Orbiter mission (EO) will perform a detailed orbital exploration of Jupiter's moon Europa to determine the presence of liquid water under the icy surface. An ARPS based upon Stirling engine technology is currently baselined for this mission. The Pluto Kuiper Express mission (PKE), planned for launch in 2004 to study Pluto, its moon Charon, and the Kuiper belt, is baselined to use a new RTG (F-8) assembled from parts remaining from the Cassini spare RTG. However, if this unit is unavailable, the Cassini spare RTG (F-5) or ARPS technologies would be required. Future missions under study may also require ARPS technologies. Mission studies are now underway for a detailed exploration program for Europa, with multiple mission concepts for landers and future surface and subsurface explorers. For the orbital phase of these missions, ARPS technologies may provide the necessary power for the spacecraft and orbital telecommunications relay capability for landed assets. For extended surface and subsurface operations, ARPS may provide the power for lander operations and for drilling.

Other missions under study may require ARPS technologies. Saturn Ring Observer (SRO) will perform a detailed study of Saturn's rings and ring dynamics. The Neptune Orbiter (NO) mission will perform a detailed multi disciplinary study of Neptune. Titan Explorer (TE) will perform in-situ exploration of Saturn's moon Titan, with both orbital operations and landed operations enabled by ARPS technologies. All of these missions would be enabled by ARPS technology.

This paper presents the current status of ongoing studies of future ESS mission concepts and the design assumptions and capabilities required from ARPS technologies. Where specific capabilities have been assumed in the studies, the results are presented along with a discussion of the implementation alternatives. No decision on power sources would be made until after completion of an Environmental Impact Statement for each project.

INTRODUCTION

Outer planets missions have few options for power generation. Solar power can be used for certain types of missions, constrained to an operational limit of about 4 AU. For missions beyond that limit, Radioisotope Thermoelectric Generators (RTGs) have been the preferred power source, providing reliable service to many missions including Voyager, Galileo and Cassini. Future deep space missions may also rely upon RTGs and the next generation of Radioisotope Power Systems (RPS). These missions represent the highest priority science objectives in the Solar System Exploration theme, and are heavily biased towards orbital and in situ investigations. The development of a robust, next generation capability for deep space power systems is enabling for these missions.

MISSION OVERVIEW

The exploration of the solar system is a continuing quest to probe the mysteries of the other planets and solar system bodies. The Exploration of the Solar System (ESS) theme has defined a set of strategic missions that represent the highest priority science opportunities for planetary investigation. In the near term, two missions are currently under development. Europa Orbiter (EO) will perform an intensive study of the Jovian moon Europa, and Pluto Kuiper Express (PKE) will perform a flyby encounter with Pluto. In the midterm and far term the strategic missions are Venus Surface Sample Return (VSSR), Europa Lander (EL), Titan Explorer (TE), Saturn Ring Observer (SRO), Comet Nucleus Sample Return (CNSR) and Neptune Orbiter (NO). Based on preliminary studies, those missions with a target of an outer planet or satellite (EO, PKE, EL, SRO, TE and NO) appear to require a RPS to provide power. The following is an overview of the mission capability needs with a summary of the power needs in flight.

Near Term Missions

The Europa Orbiter and the Pluto Kuiper Express missions form the core of the near term ESS exploration set. Combined with Solar Probe (a Sun Earth Connection [SEC] mission), the Outer Planets/Solar Probe (OPSP) program has been formed to develop common architectures and key flight systems. By exploiting the commonality among the missions, savings can be accrued in the development cycle.

Europa Orbiter

The Europa Orbiter (EO) mission is currently planned to launch in 2006. The spacecraft will take 3.25 years to reach Jupiter on a ballistic trajectory, where it will capture into Jovian orbit using chemical propulsion. In order to reduce energy necessary to get into European orbit, the spacecraft will spend two years performing multiple flybys of the Galilean satellites in what is known as the pumpdown tour. After the tour, the spacecraft will capture into European orbit using chemical propulsion, then spend two weeks performing intensive remote sensing observations. Total mission duration is approximately 5.1 years.

Current analysis indicates that a RPS is required for Europa Orbiter. Baseline plans are to employ three RPS using Stirling engine technology for power conversion, producing a total of 306 We at launch. Each RPS would consist of two GPHS modules and two Stirling engines, with the engine conversion efficiency estimated at 26.8%. The power decay over the lifetime of the mission is 9%, with the EOL power of approximately 278 We.

Pluto Kuiper Express

Pluto Kuiper Express (PKE) mission is planned to launch in 2004 on a ballistic trajectory to Jupiter. At Jupiter it will perform a gravity assist maneuver to gain energy and put it on the final trajectory to intercept Pluto. Total flight time to Pluto is on the order of 10 years (final mission architecture is still TBD) with a post encounter data playback and Kuiper belt investigation extending the mission to approximately 12 years.

Originally baselined to employ an Alkali Metal Thermal-to-Electric Converter (AMTEC) RPS, it was realized that AMTEC would not be available to meet the planned launch schedule. The most likely alternative for powering the spacecraft is a new RTG (known as the F-8 made up of Cassini RTG spare parts). This RTG would be expected to produce 290 We of power at launch and would degrade to 231 We by the end of the mission.

The power critical mode for the mission is encounter, where all instruments will be powered on and operating. In this mode the estimated total spacecraft power draw is 256 W. An auxiliary battery will be included and will draw down to approximately 70% DOD during the encounter operations.

Strategic Missions

The strategic missions are midterm and far term missions (2008 – 2020 launch) and represent the highest priority science opportunities in the ESS theme. Mission studies have been performed to scope the mission architecture and flight system requirements to meet the science objectives. The following is an overview of the missions and their power needs.

Europa Exploration

The future exploration of Europa (after Europa Orbiter) concentrates on surface and subsurface exploration. If Europa Orbiter finds compelling evidence of water on Europa, the next significant effort will be to place a lander upon the surface with an appropriate payload. The primary scientific goals of the proposed Europa Lander mission are to characterize the surface material from a recent outflow and look for evidence of pre-biotic and possibly biotic chemistry. The baseline mission concept involves landing a single spacecraft on the surface of Europa with the capability to acquire samples of material, perform detailed chemical analysis of the samples, and transmit the results to Earth.

The mission architecture is based upon a single vehicle consisting of a propulsion module, or carrier, and the lander. The Lander contains the bulk of the flight systems, including the power supply and electronics. The carrier contains the chemical propulsion elements necessary to inject into Jovian orbit. Europa Lander would perform the same pumpdown tour of the Galilean satellites to get into orbit of Europa. After the tour the carrier stage is discarded prior to entry and landing.

Surface operations are limited due to the thermal and radiation environment. The ARPS would power the surface payload package and surface operations. The primary science objectives are to analyze surface material from at least 0.5m depths for prebiotic and biotic compounds, and to characterize the geophysical and geochemical environment. Integral to this mission will be a drilling and sample handling system for the extraction of samples and processing for analysis. Additional payload will provide analysis of the surface and monitoring of the seismic environment.

Titan Explorer

The Titan Explorer study is intended as a broad look at Titan exploration after Cassini/Huygens. Titan is an organic rich satellite of Saturn. This mission investigates the surface environment with the intent to understand the distribution and composition of organics and the geological and geophysical processes that contributed to the evolution of Titan's prebiotic chemistry. The science objectives are to study distribution and composition of organics in the atmosphere, on the surface, and below the surface, to study the role of geological and geophysical processes and evolution in Titan's prebiotic chemistry and to investigate the dynamics, meteorology, cloud formation, and interactions of Titan's atmosphere with its diverse surface. Both aerobot and rover missions for Titan in-situ exploration has been considered. Additionally, an arover mission, a mission whose science return is a combination of the global aerobot science and the local rover science is being considered.

The first mission studied was an aerobot mission. As envisioned here, the term aerobot describes a balloon system that utilizes a condensable inflating fluid to control its altitude while drifting downwind. A strawman payload was selected based on our current knowledge of Titan and instruments that are currently available or under development. Operationally, this is a global reconnaissance mission. Current knowledge of the winds leads us to expect that the aerobot could circle Titan every couple of weeks. The expected operational lifetime is about a month. The aerobot payload would continuously image and collect point spectra which it would use to decide where to sample. Radar would provide surface altimetry information. Samples would be collected by dropping a sampling device on a line and then reeling it in for analysis by a suite of instruments in the gondola. Wide- and narrow-angle imagery would be obtained of the sampling site. Both powered (steerable) and unpowered aerobots were considered.

The rover mission was assumed to have a surface range of several kilometers. The rover payload was a functional copy of the aerobot payload with seismometry and heat flow added. Sampling on the rover includes the capability to collect 10-cm cores for analysis by the instruments. The rover could operate largely autonomously or could be directed from the ground as in the Pathfinder mission. There would also be the possibility of resampling if an analysis proved to be of particular interest. The rover lifetime would be several months.

The Aeroover mission is a combination of the aerobot and rover missions that initially performs the aerobot mission and then performs a rover mission. It was suggested that this could be accomplished with an inflatable-wheeled rover by over-inflating the wheels to provide aerobot buoyancy. This system would be robust for a variety of surface conditions. The mission would include a thirty day aerobot phase followed by a thirty day rover phase.

All of the point design mission concepts use a six -year indirect solar electric propulsion (SEP) transfer trajectory from Earth to Saturn launching in 2008. Upon arrival at Saturn the orbiter and lander enter together directly into the atmosphere of Titan, where a ballute (a hypersonic drag device) decelerates the spacecraft. At appropriate velocity, the orbiter separates and the lander continues to decelerate for entry. Power for the orbiter/carrier would be provided by two ARPS producing 212 We total at BOL. For surface operations, a single ARPS would be needed for all options.

Additional surface mobility options have been proposed for Titan Exploration. In order to meet the science objectives of multiple samples while maintaining geographical diversity, various heavier than air options have been proposed. In all study cases, the power required has been provided by some form of ARPS technology.

Saturn Ring Observer

The Saturn Ring Observer is an ambitious concept to place a spacecraft in close proximity to Saturn's rings. This mission will study the rings and ring particles to better understand ring processes and evolution as a model for the origin of planetary systems. This will involve measurement of ring particle physical properties, dynamics and spatial distribution. The science objectives are to make direct observations of the physical properties of the ring particles, kinematic processes in the rings, including velocity components in all 3 directions, scale height, coefficient of restitution in typical collisions, clumping/sliding/shearing behavior of particle agglomerations and the spin states of ring particles.

A baseline mission concept has been developed. The primary arrival time at Saturn begins in 2014 and continues through 2020, which corresponds to the maximum opening angle of the rings as seen from Earth. A point design trajectory has been defined that provides a 9-yr flight time with a 2008 launch (2017 arrival). The initial trajectories examined were low thrust Solar Electric Propulsion (SEP) trajectories, although ballistic trajectories and solar sail options have been investigated. Several options have been examined relative to the insertion scenario at Saturn. The implementation chosen uses a ballute single-pass aerocapture followed by a direct insertion above the Huygen's gap at apoapsis. This is a high technology scenario, but has the least required propulsive ΔV of all the scenarios (approximately 4590 m/s). The insertion is staged, using a separable chemical stage to deliver the ring observer to station. Once delivered, the ring observer spacecraft executes altitude maintenance above the ring plane and provides radial excursion capability. Science operations are scheduled for one month following insertion. The mission concept calls for placing the spacecraft in a ring-particle-like orbit with a very small inclination to the ring plane and then using four small plane change maneuvers per orbit to stay approximately 3 km above the plane. In effect, the spacecraft hovers above a particular point on the ring. Propellant is budgeted to make four changes in radial position after the initial orbit insertion.

System power for the spacecraft would be provided by a combination of the ARPS and the solar arrays. The flight system consists of three stages, the SEP stage, a chemical propulsion interstage and the ring orbiter spacecraft. After launch, the SEP stage provides the required ΔV to reach the planet. This stage completes its mission at 2.7 AU and is jettisoned. Prior to jettison, the solar arrays provide power to the whole flight system. Following the jettison, power is provided by two ARPS, providing 212 We at BOL. The maximum power mode for the ARPS is during science operations, where all the science instruments are powered.

Neptune Orbiter

The Neptune Orbiter mission is the next evolutionary step in the intensive study of the outer planets. Following in the heritage of Galileo and Cassini, the Neptune Orbiter mission will perform an intensive study of the Neptunian system from orbit. The overall science goals of the Neptune Orbiter Mission are to study the rings, ring arcs, and shepherd satellites over a period of at least two years, perform intensive studies of Triton's surface and atmosphere, examine Neptune's atmosphere and magnetosphere, and study the satellites Larissa, Proteus and Nereid.

A minimum energy transfer from Earth to Neptune would require more than 30 years, which is too long for a planetary mission. A number of alternatives to a direct transfer were examined. A Jupiter flyby (JGA) offers the most gain of the impulsive/ballistic trajectory alternatives; such a transfer is available for Earth departures in 2005, 2006, and 2007 and then not again until about 2017. A direct JGA transfer leaving in 2007 was selected as a baseline mission, with several solar electric propulsion (SEP) options considered for launches later than 2007. The spacecraft would employ aerocapture at Neptune to capture into orbit and would spend at least 2 years in orbit.

The orbiter would employ two ARPS providing 212 We at BOL. The maximum power mode for the ARPS is during the data transmission modes from the spacecraft to Earth.

Power Modes Summary

Table 1 and table 2 provides a summary of the significant power modes for the Cruise Stage/Orbiter for all missions. Table 2 provides the information for landed vehicles and surface operations. These estimates were based upon reasonable approximations of payload and mission operations.

TABLE 1. Power mode summary for Cruise Stage/Orbiters

Cruise Stage/Orbiter	Power Mode (We)					RPS Comments
	Launch	Cruise	Encounter	Science	Other *	
Europa Orbiter	160.3	204.0	304.2	228.9	-	Stirling Converters
Pluto/Kuiper Express	120.9	132.2	182.3	154.4	-	F-8 RTG
Europa Lander (Carrier)	-	78.5	205.1 ^a	-	-	RPS on lander
Neptune Orbiter	123.7	114.1	80.7	101.1	147.6 (TX)	AMTEC – 4GPHS (212We BOL)
Saturn Ring Observer	121.2	44.6	52.0	158.1	146.5 (TX)	AMTEC – 4GPHS (212We BOL)
Titan Explorer (Carrier)	183.6	152.3	49.4	162.5	-	AMTEC – 4GPHS (212We BOL)

^a Li-Ion battery to provide additional power for these modes

TABLE 2. Power mode summary for Landers

Landed Vehicles	Power Mode (We)					RPS Comments
	Entry	Mobility	Sample collection	Sample Analysis	Data TX	
Europa Lander	237.3 ¹	-	56.0	109.8	205.1 ^a	AMTEC – 4GPHS (212We BOL)
Titan Explorer (Aerobot)	52.3	30.1	57.8	58.0	58.4	AMTEC – 2GPHS (106We BOL)
Titan Explorer (Rover)	49.4	76.4	70.5	76.4	75.8	AMTEC – 2GPHS (106We BOL)
Titan Explorer (Aerover)	9.0	75.5	56.3	62.2	62.8	AMTEC – 2GPHS (106We BOL)

^a Li-Ion battery to provide additional power for these modes

ACKNOWLEDGMENTS

The author wishes to acknowledge the efforts of the many individuals that supported these studies. In particular, the authors wish to acknowledge the Team X study team and George Cancro of the Outer Planets/Solar Probe Project. The research described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology under contract with the National Aeronautics and Space Administration.

REFERENCES

- Team X Study Report, *Neptune Orbiter, 4-99 SSE Roadmap Review*, JPL Study Report, dated 15 April 1999
- Team X Study Report, *Saturn Ring Observer, 4-99 SSE Roadmap Review*, JPL Study Report, dated 16 April 1999
- Team X Study Report, *Titan Lander, 4-99 SSE Roadmap Review*, JPL Study Report, dated 29 April 1999
- Team X Study Report, *Europa Lander, 4-99 SSE Roadmap Review*, JPL Study Report, dated 13 April 1999
- Team X Study Report, *Europa Lander, 5-99*, JPL Study Report, dated 4 May 1999
- Gershman, R., Nilsen, E., and Oberto, R., *Europa Lander*, IAA-L-0603, Fourth IAA International Conference on Low-Cost Planetary Missions, May 2-5, 2000
- Gershman, R., Nilsen, E., and Wallace, R., *Neptune Orbiter*, IAA-L-0603, Fourth IAA International Conference on Low-Cost Planetary Missions, May 2-5, 2000